Wide Bandgap Extrinsic Photoconductive Switches

J. S. Sullivan and J. R. Stanley

Abstract— **Semi-insulating Silicon Carbide and Gallium Nitride are attractive materials for compact, high voltage, photoconducting semiconductor switches (PCSS) due to their large bandgap, high critical electric field strength and high electron saturation velocity. Carriers must be optically generated throughout the volume of the photoswitch to realize the benefits of the high bulk electric field strength of the 6H-SiC (3 MV/cm) and GaN (3.5 MV/cm) materials. This is accomplished by optically exciting deep extrinsic levels in Vanadium compensated semi-insulating 6H-SiC and Iron compensated semi-insulating GaN. Photoconducting switches with opposing electrodes were fabricated on a-plane, 6H-SiC substrates and c-plane, GaN substrates. This work reports what we believe to be the first results of high power photoconductive switching in bulk, semi-insulating GaN and reviews the first phase of switch tests of a-plane, 6H-SiC PCSS devices.**

***Index Terms*—Photoconducting devices, photoconductivity, light triggered switches, semiconductor switches, silicon carbide, gallium nitride.**

I. INTRODUCTION

6H-SiC and 2H-GaN have wide band-gaps (3.0 - 3.4 eV), high critical field strength (3.0 - 3.5 MV/cm) and high-saturated electron velocity (2.0 - 2.5x10^7 cm/s). These material properties make semi-insulating 6H-SiC and GaN attractive semiconductor materials for the Photoconductive Semiconductor Switch (PCSS) application. Previous SiC PCSS work [2-5] used high resistivity, low impurity SiC polytypes and focused on lateral geometry surface switches that used above band-gap wavelengths of light to trigger the switches. Previous work [6] on a GaN photoconducting switch used a thin (1 μm) epitaxial layer of Carbon doped GaN as the active region of a large aperture photoconductive switch (LA-PCSW) for subterahertz electromagnetic wave radiation. This GaN LA-PCSW device was constructed in the lateral geometry, triggered with above bandgap light and switched four to five hundred μA at a bias voltage of 250 V. The performance and switch life of lateral geometry PCSS are limited by surface flashover, surface carrier mobility and high current density. PCSS with opposing electrical contacts deposited on Vanadium compensated, semi-insulating, 6H-SiC, and Iron compensated, semi-insulating 2H-GaN bulk substrates can be triggered using below band-gap light to excite carriers from extrinsic levels throughout the volume of the material. This results in diffuse photocurrent and switch hold off voltages determined by the bulk breakdown field strength of the 2H-GaN and 6H-SiC materials. The bulk switching capability and semi-insulating nature of 6H-SiC and 2H-GaN are enabled by the addition of the dopants vanadium and Iron. Vanadium is an amphoteric impurity that can act as a deep acceptor, or a deep donor in 6H-SiC. Vanadium acts as a deep acceptor when the nitrogen donor impurity density sufficiently exceeds the boron acceptor impurity density, which is the case for the 6H-SiC material we have tested. The Fermi level is pinned close to the Vanadium acceptor level (0.7 eV below conduction band) resulting in a semi-insulating material. The Vanadium acceptor levels capture electrons donated from the shallow (0.08 eV below conduction band) Nitrogen donor levels. These captured electrons can be excited into the conduction band by photons with energies exceeding 0.7 eV. Figure 1 [7] depicts the extrinsic levels in the 6H-SiC bandgap. The Boron acceptor levels and defect levels are also shown in Figure 1. The defect levels include Silicon vacancies and the UD-1 defect [7]. GaN utilizes an Iron acceptor level (0.5 – 0.6 eV below the conduction band) to compensate shallow Oxygen donors. Electrons that are captured by the Iron acceptor levels can be excited into the conduction band by photons with energies greater than 0.6 eV.

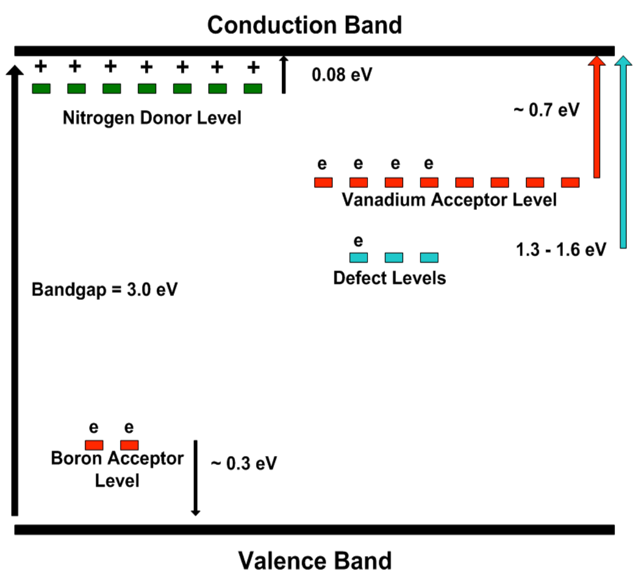

Fig. 1. Vanadium acceptor and nitrogen donor levels in vanadium compensated 6H-SiC.

II. PHYSICAL LIMITATIONS OF EXTRINSIC PCSS

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An ideal switch should hold off high voltage in the off state, have negligible resistance in the on state, be easy to trigger and as small as practical. Extrinsic PCSS fabricated from 2H-GaN and 6H-SiC offer hold off voltages limited only by the critical fields of the materials (3.0 – 3.5 MV/cm) and the enhancement factor of the switch electrode geometry. A single 6H-SiC, 400 μm thick, PCSS assembly was tested to catastrophic electrical failure [1] at a charge voltage of 11.0 kV. Breakdown occurred at the edge of the electrode metalization, the point of maximum field enhancement. A peak electric field in excess of 2.3 MV/cm was predicted for the PCSS failure point using an electrostatic numerical modeling code that included the effects of electrode geometry and Indium solder meniscus. We believe that 6H-SiC PCSS devices based on 1 mm thick substrates can reliably hold off tens of kilovolts with proper control of field enhancements.

The switch on resistance of 6H-SiC and 2H-GaN extrinsic PCSS is limited by the number of carriers that are trapped in extrinsic levels of the material and the active area of the device. The carriers trapped in the extrinsic levels in 6H-SiC extrinsic PCSS are limited to the 10^{16} – $10^{17}/cm^3$ range due to the maximum solubility of 3 – $5x10^{17}/cm^3$ of Vanadium in 6H-SiC. However, carrier levels of 10^{16} – $10^{17}/cm^3$ are sufficient to achieve an on resistance of a few hundred milliohms, or less, for a 1mm thick, 1 cm^2 switch.

Applying an optical pulse of sufficient energy to one, or more, of the PCSS facets, triggers the switch. Currently, 10 –13 mJ of optical energy is required to trigger both the 6H-SiC and 2H-GaN devices. The optical trigger pulse can be coupled into the facet of the PCSS by fiber optic, optical waveguide, or direct illumination by a laser. An advantage of optical triggering is complete isolation between the trigger system and high voltage circuit.

The physical size of the switch is determined by the required hold off voltage (substrate thickness), switch on resistance (active area) and the penetration depth of the optical trigger pulse. Optical penetration depth in 6H-SiC and 2H-GaN at the 532 and 1064 nm wavelengths will be discussed in section IV.

III. 6H-SiC SWITCH TEST RESULTS

A detailed presentation of the 6H-SiC switch test results has been previously reported [1]. Here we will present a brief review. Six PCSS devices were fabricated from samples of 400 μm thick, 1.2 cm per side, square substrates of "a" plane, vanadium compensated, semi-insulating 6H-SiC. The four facets of the substrate were cleaved/polished to enhance optical coupling into the bulk of the substrate. The contacts consist of a 0.8 cm diameter, circular metalization centered on opposing sides of the substrate. The metalization formed an ohmic contact and consisted of layers of nickel, titanium, platinum and gold. The metal deposition and anneal were performed at SemiSouth Laboratories Inc. in Starksville, MS. Indium coated copper electrodes were brazed to the substrate metalizations to facilitate electrical connection. The finished 6H-SiC PCSS assembly is shown in Figure 2.

Photoconductivity tests were performed using 1064 nm and frequency doubled 532 nm wavelength light from a Q-switched Nd:YAG laser with an 8 ns at full wave half maximum (FWHM) output pulse. The optical pulse was focused and aligned to obtain as uniform as possible light pulse over a rectangular area measuring 1 cm wide by 400 μm high. The optical pulse was then centered on the PCSS facet.

Fig. 2. Vanadium compensated, semi-insulating, 6H-SiC PCSS assembly.

Photoconductivity tests were performed using optical pulse energies ranging from 1 to 14 mJ. The photoconductivity of the PCSS was measured using the circuit shown in Figure 3. The 1.5 μF capacitor of the test circuit was pulse charged to bias voltages ranging from 250 V to 4.25 kV in 30 μs and the PCSS was optically triggered after a 30 μs flat top interval of the pulse bias voltage for the 6H-SiC device. The voltage across the PCSS was measured differentially using a pair of calibrated, fast (250 MHz bandwidth), high voltage (5 kV) probes. The load voltage was measured using a fast (35 ps rise time), low impedance (250 Ω) high voltage probe. The PCSS current was obtained by dividing the load voltage by the load resistance. Dynamic switch resistance is another important switching parameter. The dynamic switch resistance is calculated by dividing the switch voltage by the load current.

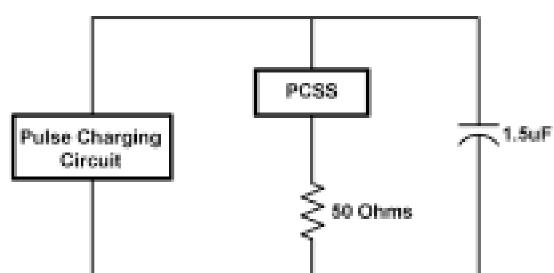

Fig. 3. Simple schematic for PCSS photoconductivity test circuit.

The PCSS voltage and current for a 4.25 kV charge voltage and optical pulse energy of 13 mJ at 1064 nm are shown in Figure 4. The PCSS voltage starts at 4.25 kV and collapses to approximately 750 Volts in 10 ns, while the PCSS current increases from zero to 70 A. The PCSS current pulse is similar in temporal profile to the 1064 nm optical trigger pulse. However, the photocurrent has a 16 ns FWHM pulse-width indicating a carrier recombination time of a few nanoseconds, or, less. The minimum dynamic PCSS resistance for the pulse shown in Figure 4 is 11 Ω. The minimum dynamic PCSS resistance is approximately constant for fixed optical pulse energy, regardless of the charge voltage. Switch minimum dynamic PCSS resistance as a function of optical pulse energy for 1064 and 532 nm wavelengths is shown in Figure 5. The switch minimum dynamic PCSS resistance decreases rapidly with optical pulse energy for both optical wavelengths. The PCSS attains a lower minimum dynamic resistance at all optical energies for excitation with 532 nm light compared to excitation with 1064 nm light. This is a result of charge carriers being excited from additional extrinsic levels by the 532 nm wavelength.

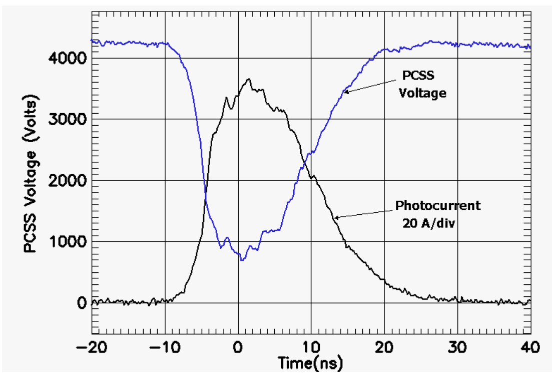

Fig. 4. PCSS voltage and current for bias voltage of 4.25 kV and 13 mJ optical trigger at 1064 nm.

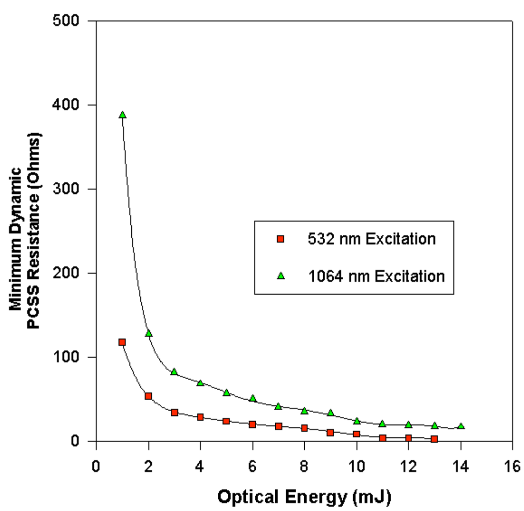

Fig. 5. Minimum dynamic PCSS resistance, as function of optical trigger energy, for 532 and 1064 nm.

IV. SiC and GaN Transmission Measurements

Two different optical transmission measurements were performed on 6H-SiC and 2H-GaN substrates. A Cary 5000 spectrophotometer was used to measure transmission through the 400 μm dimension of the 6H-SiC and 2H-GaN substrates at low intensities over the spectral range of 300 to 1200 nm. It is reasonable to neglect all but linear optical absorption in the bulk SiC and GaN substrates at the low intensities applied by the spectrophotometer. The spectrophotometer results were used to calculate the effective linear absorption of 6H-SiC and 2H-GaN at 532 and 1064 nm using equation (1), assuming linear absorption and measured values of the index of refraction [8,9] for both materials. We calculated the values of effective linear absorption to be 1.61 and 0.63 cm^{-1} for 6H-SiC, and 0.43 and 0.10 cm^{-1} for GaN at the 532 and 1064 nm wavelengths, respectively.

$$T = \frac{(1-(\frac{n-1}{n+1})^2)^2 \exp(-\alpha l)}{1-(\exp(-\alpha l)(\frac{n-1}{n+1})^2)^2} \qquad (1)$$

Where T is the transmission, α is the effective linear absorption, l is the length traveled through the substrate and n is the index of refraction of either 6H-SiC or GaN.

If sufficiently high optical intensities are applied, sources of nonlinear optical absorption need to be considered. The differential equation describing the optical loss in a bulk material is given by equation (2).

$$dI/dz = -\alpha I - \beta I^2 - \sigma_c N_c(I) I \qquad (2)$$

Where I is the optical intensity, β is the two photon absorption coefficient, σ_c is the free carrier cross-section and N_c is the free carrier density.

High power optical transmission measurements were performed on a 7.2 mm by 3.7 mm, 400 μm thick, 6H-SiC substrate and a 9.0 mm by 9.0 mm, 408 μm thick, 2H-GaN substrate. The optical pulse passed through a 50/50 beam splitter and half the pulse was applied to a SiC, or GaN, substrate facet and the other half was applied to an optical energy meter. Optical pulses were applied to the 3.7 mm by 400 um facet of the 6H-SiC substrate with the optical E field perpendicular to the c direction of the SiC growth crystal. For the GaN substrate, the optical pulse was applied to the 9.0 mm by 408 μm facet with the optical E field vector parallel to the c direction of the GaN crystal. Both substrates were masked so that only light striking the facet was transmitted to an optical energy meter positioned behind the substrate. The effective absorption was calculated from the transmission measurements using equation (1) assuming only linear absorption in the bulk material. We expect the effective absorption coefficient to be constant as the applied optical energy is increased, if only linear absorption were taking place in the material. If the effective optical absorption coefficient increases with applied intensity, this indicates that the two photon, or, free carrier absorption terms in equation (2) are contributing to the optical loss.

Plots of the effective absorption coefficient as a function of optical energy are shown in Figure 7. The optical penetration depth ($1/\alpha$) for a 10 mJ optical pulse at 532 nm is 0.47 and 0.57 cm for 6H-SiC and 2H-GaN, respectively. The optical penetration depth is a limitation on switch active area and overall switch geometry since the optical trigger pulse has to penetrate into the switch material and generate carriers throughout the switch volume. It is apparent from the plots that the effective linear absorption is constant in the bulk 2H-GaN (0.35 cm^{-1}) at 1064 nm, indicating only linear absorption occurs. However, the 2H-GaN has a significant nonlinear loss component at 532 nm. 6H-SiC exhibits nonlinear loss at both the 532 and 1064 nm wavelengths. We assume that the largest nonlinear component of the absorption is free carrier absorption. A large nonlinear component in the effective absorption indicates significant free carrier density, hence a better candidate switch material. This has been verified in switching results. Both materials have lower on resistance at 532 nm. However, higher optical absorption translates to shallower optical penetration depths and limits on the size and geometry of switch structures.

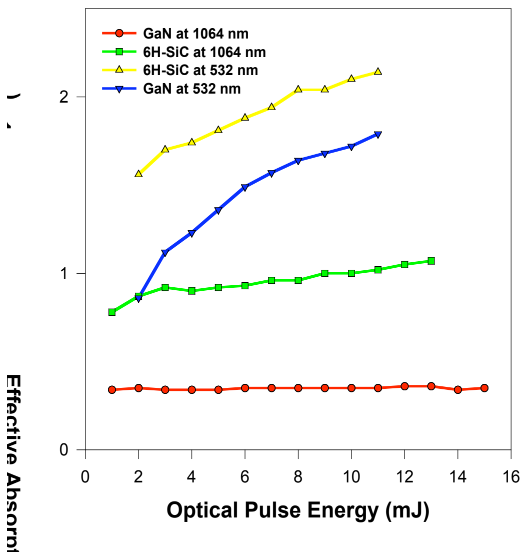

Fig. 7. Effective optical absorption in GaN and SiC at 532 and 1064 nm

V. GaN Switch Test Results

A GaN switch assembly was fabricated using a 9 mm by 9 mm, 408 μm thick, semi-insulating substrate. The GaN substrate was epitaxially grown by Kyma Technologies. 6.5 mm diameter circular metallization layers were centered on both sides of the GaN substrate. The metallization consisted of layers of Titanium and Gold deposited by a liftoff technique. Copper electrodes were brazed to the substrate metallization using Indium solder. The GaN switch assembly is shown in Figure 8. The GaN device was tested using the same circuit as the 6H-SiC devices (Fig.3) with a range of bias voltages from 150 to 1000 volts. Optical excitation at both 532 and 1064 nm were applied to the GaN switch. However, only a neglible amount of photocurrent was generated at 1064 nm. The results for excitation at 532 nm are shown in Figures 9, 10 and 11.

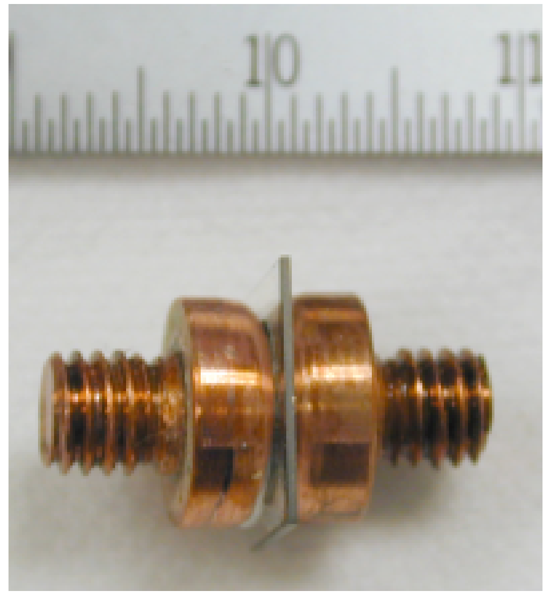

Fig. 8. GaN switch assembly (ruler scale in mm)

Figure 9 shows the GaN switch voltage, current and optical excitation for a 1000 Volt charge voltage and 12 mJ of optical excitation at 532 nm. These results were obtained for an optical pulse that measured ~ 5.5ns (FWHM), significantly shorter than the optical pulses used to excite the 6H-SiC switch (8 ns FWHM). The switch voltage begins to collapse as soon as the optical pulse is applied to the switch facet. The switch voltage decreases from 1005 to 19 Volts in approximately 7 ns. The switch current follows the optical excitation pulse and increases to 19.5 Amps during the same nanosecond period. The minimum switch on resistance is just under 1 ohm for this pulse. The switch current pulse width is 11 ns (FWHM) which is approximately twice the optical pulse width indicating a fast recombination time for this switch.

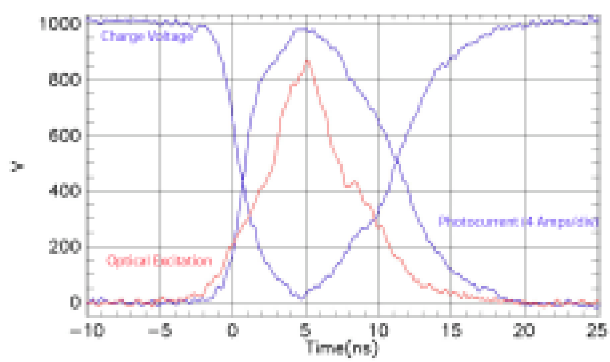

Fig. 9. Switch voltage, photocurrent and optical excitation for GaN switch at 1000 Volts charge voltage and 12 mJ excitation at 532 nm.

Figure 10 shows the peak switch photocurrent as a function of optical excitation energy at a wavelength of for a variety of charge voltages. The saturation of the photocurrent begins at 3 – 4 mJ of optical excitation for all charge voltages. The data shown in Figure 10 can be recast to show the peak photocurrent as a function of charge voltage for a range of optical excitation energies. The resulting plots are shown in Figure 11 and the linear dependence of peak photocurrent with switch voltage of the GaN switch becomes apparent. The peak photocurrent is a linear function of bias voltage for excitation with a fixed optical energy. This indicates that the total resistance of the test circuit is constant for a fixed applied optical energy. The circuit resistance calculated for a fixed applied optical energy of 0.5 and 12 mJ is 685.7 and 51.6 Ohms, respectively. The minimum GaN switch resistance is calculated by subtracting the 51 Ohm load resistance from the total circuit resistance, resulting in 634.7 and 0.6 Ohms, respectively for 0.5 and 12 mJ excitation.

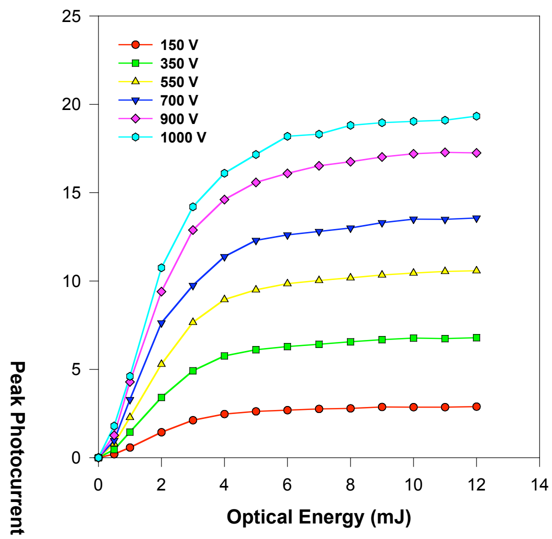

Fig. 10. Peak photocurrent of GaN switch as function of optical excitation energy for range of charge voltages of 150 – 1000 Volts.

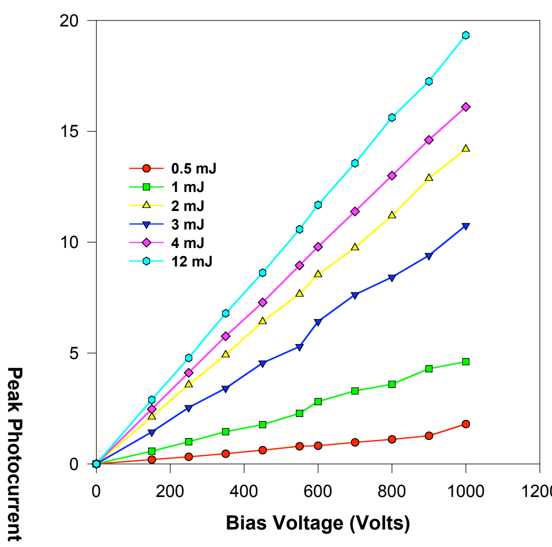

Fig. 11. Peak photocurrent vs bias voltage for a range of 0.5 – 12 mJ in optical energies.

VI. Conclusions

Linear, extrinsic photoconductive switches have been fabricated from semi-insulating 6H-SiC and 2H-GaN substrates. Minimum switch resistances of 11 and 2 –3 Ohms have been demonstrated for 6H-SiC devices at 1064 and 532 nm excitation, respectively. Minimum switch resistances of 1100 and 0.6 Ohms have been demonstrated for a 2H-GaN device at 1064 and 532 nm excitation, respectively. It appears that the shallow Nitrogen donor and deep Vanadium acceptor levels are key to the switching at 1064 nm in the 6H-SiC devices. Unknown deeper levels contribute to the photocurrent in the SiC devices at 532 nm. The expected switching action using the shallow Oxygen donor and deep Iron acceptor levels in 2H-GaN was never manifested at 1064 nm excitation. Unknown deep levels exhibited strong switching action in GaN at 532 nm excitation. Future work will be to optimize the Nitrogen and Vanadium density in 6H-SiC for switching at 1064 nm and identifying deep levels in GaN that contribute to switching at 532 nm.

VII. References

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